

51-45  
64287  
p.18  
N92-19122

## Chapter 2

# High-Speed Civil Transport Aircraft Emissions

R. C. Miake-Lye  
Aerodyne Research, Inc.  
Billerica, MA

### Contributors

J. A. Matulaitis, F. H. Krause, W. J. Dodds  
GE Aircraft Engines  
Cincinnati, OH

M. Albers and J. Hourmouziadis  
MTU Motoren-und Turbinen Union  
Munchen, Federal Republic of Germany

K. L. Hasel and R. P. Lohmann  
Pratt & Whitney  
East Hartford, CT

C. Stander and J. H. Gerstle  
Boeing Commercial Aircraft Company  
Seattle, WA

G. L. Hamilton  
McDonnell Douglas Aircraft Company  
Long Beach, CA

## ABSTRACT

Estimates are given for the emissions from a proposed high-speed civil transport (HSCT). This advanced-technology supersonic aircraft would fly in the lower stratosphere at a speed of roughly Mach 1.6 to Mach 3.2 (470 to 950 m/sec or 920 to 1,850 knots). Because it would fly in the stratosphere at an altitude in the range of 15 to 23 km commensurate with its design speed, its exhaust effluents could perturb the chemical balance in the upper atmosphere. The first step in determining the nature and magnitude of any chemical changes in the atmosphere resulting from these proposed aircraft is to identify and quantify the chemically important species they emit.

This chapter summarizes relevant earlier work, dating back to the Climatic Impact Assessment Program (CIAP) studies of the early 1970s and current propulsion research efforts at NASA and at its High-Speed Research Program (HSRP) contractors' laboratories. Recent work funded by HSRP is providing estimates of the chemical composition of an HSCT's exhaust, and these emission indices (EIs) are presented. Other aircraft emissions that are not due to combustion processes are also summarized; these emissions are found to be much smaller than the exhaust emissions. Future advances in propulsion technology, in experimental measurement techniques, and in understanding of upper-atmospheric chemistry may affect these estimates of the amounts of trace exhaust species or their relative importance, and revisions will probably be necessary in the future.

## INTRODUCTION AND BACKGROUND

The upper atmosphere has been perturbed by anthropogenic chemicals. Most notable of these are the chlorofluorocarbons (CFCs), which are implicated in the depletion of stratospheric ozone and the creation of the Antarctic ozone hole. Because of the variety of technical advantages they offered, these chemically inert species were developed for industrial processes and consumer products before it was realized that they were photo-chemically reactive in the upper atmosphere. A full understanding of the detailed chemical balance and how it is affected by perturbations caused by pollutants is still being developed. Because of this awareness of the anthropogenic effects on the stratosphere, the exhaust emissions from the proposed HSCTs are being analyzed.

The exhaust species under most extensive scrutiny at present are the oxides of nitrogen, NO and NO<sub>2</sub>, collectively denoted as NO<sub>x</sub>. The potential for catalytic destruction of ozone by exhaust NO<sub>x</sub> in the stratosphere was recognized (1) in the early 1970s, when the U.S. supersonic transport (SST) was being studied. The Climatic Impact Assessment Program (CIAP) was undertaken to consolidate and extend existing knowledge of the chemistry, physics, and technology of supersonic flight in the stratosphere and the effects of the consequential exhaust emissions. The results and conclusions of that program are summarized in its proceedings (2-5) and monographs (6-11). The state of knowledge and technology on aircraft emissions, as of 1975, is presented in the CIAP Monograph 2 (7), "Propulsion Effluents in the Stratosphere."

Aircraft propulsion technology has advanced in the intervening years such that the reasons the U.S. SST was not considered viable can now be addressed with technical improvements (12-14). The evolution of such technically improved engines has actually made NO<sub>x</sub> reduction more difficult, as the combustor pressure and temperatures have risen to improve propulsion efficiency. Yet, reduction of NO<sub>x</sub> levels below that achieved with SST-era technology appears to be necessary to avoid major stratospheric ozone depletion. To achieve this, combustors must be improved, requiring the results from current research aimed at controlling local temperatures and equivalence ratios throughout the combustion process. A pivotal ques-

tion concerns the quantitative effects on the atmosphere of the reduced levels of exhaust trace species emitted from the advanced-technology propulsion systems that would power the proposed HSCT.

The understanding of stratospheric chemistry and transport has also made enormous strides. The role of heterogeneous chemistry, in particular, was not apparent when commercial stratospheric flight was last considered. An awareness of chemistry on the surface of condensed water and/or condensed aqueous solutions has grown out of the need to understand the Antarctic ozone hole. Now, this heterogeneous chemistry must be accounted for in the global stratospheric chemical balance; it also must be assessed for a possible role in the wake of stratospheric aircraft. In the aircraft wake, the locally high (relative to ambient concentrations) trace-species concentrations may encounter condensed water in the condensation (contrails) in the exhaust behind the aircraft.

Additional data concerning condensation nuclei (CN) emitted by the aircraft are required for understanding the possible role of heterogeneous chemistry, both globally and in the wake. These CN are essential for the formation of contrails, and their number density affects the contrail particle sizes and number densities. The chemical nature of the CN surfaces controls their ability to condense water: typically, newly formed soot has a small fraction of its number density as active CN. The CN, in the form of ambient condensed sulfate particles, exhaust carbonaceous soot particles, and possibly other exhaust particulates are critical for initiating the condensation process that can occur, under some conditions, in the proposed stratospheric flight paths. Measurements of CN number densities and knowledge of their condensation properties are necessary to predict droplet lifetimes and settling distances and, thus, their role in wake chemistry and transport and in global stratospheric aerosol loading.

Once a condensed surface is present, additional chemical species must be accounted for, and additional chemical reactions occurring on the condensed phase/vapor interface must be introduced in the overall chemical balance.  $\text{HNO}_3$  and  $\text{N}_2\text{O}_5$ , formed by further reactions of  $\text{NO}_x$ , have been shown to figure prominently in the heterogeneous chemistry occurring in the polar stratospheric clouds that drive the Antarctic ozone hole. These species could also react with aerosols in the contrail, if and when concentrations of species and particles are high enough for sufficiently long durations.

The list of chemically relevant exhaust species now goes beyond the major combustion products of  $\text{CO}_2$  and  $\text{H}_2\text{O}$  and the trace species  $\text{NO}_x$ . A fuller set of "odd-nitrogen" compounds, termed  $\text{NO}_y$ , including  $\text{NO}_x$ ,  $\text{NO}_3$ ,  $\text{N}_2\text{O}_5$ ,  $\text{HNO}_3$ , and (although not an exhaust species)  $\text{ClONO}_2$ , must be considered as aerosol-active species, in addition to  $\text{SO}_2$  and soot particles. The total unburned hydrocarbons (THC) and CO in the exhaust represent combustion inefficiencies and play a role in important stratospheric  $\text{HO}_x$  ( $\text{OH}$ ,  $\text{HO}_2$ ) chemistry.

The techniques used to measure these species will be discussed in the next section, followed by a brief summary of how engine emissions are being projected for the next generation of low  $\text{NO}_x$ , sustained supersonic propulsion systems. The projected estimates will be discussed in a following section and compared with past measurements on related, predecessor engines. Finally, a set of estimates for emissions from the aircraft that are not a result of the propulsion system will be reviewed.

## MEASUREMENT APPROACHES

Quantitative measurements of exhaust emissions are carried out only in ground-based facilities. In fact, emissions have rarely been measured during aircraft flight, and then, only qualitative results were obtained (15-17). Ground-based measurements of entire engines must

be performed in a test facility that can reproduce ambient conditions, including pressure and temperature, if quantities appropriate to high-altitude flight are to be measured. Such tests are exceedingly expensive (18) and require considerable preparation and support, so there is strong motivation to perform simpler measurements on components of the engine separately in smaller laboratory-based facilities.

Primarily, these simpler measurements consist of reproducing the flow conditions in a trial combustor, or a simplified version of one, and making measurements at its exit. The flow into and out of the combustor can be calculated reliably for a chosen engine cycle. The more benign conditions encountered during laboratory component testing increase the accuracy of individual measurements.

Most gaseous species are measured using continuous-sampling probes that take a small volume of the exhaust-gas flow from the component to the measurement instrument, controlling the temperature and flow velocity, and thus the delay until time of measurement. The species currently being measured routinely include  $\text{CO}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{CO}$ ,  $\text{NO}$ ,  $\text{NO}_2$ ,  $\text{SO}_2$ , and the THC (19-20), both as an undifferentiated sum of total C and as individual hydrocarbon species in more detailed batch sampling studies (21-23). Batch samples are analyzed using gas chromatography and/or mass spectroscopy to quantify the various hydrocarbon species present, as well as  $\text{H}_2$ ,  $\text{O}_2$ ,  $\text{N}_2$ ,  $\text{CO}$ , and  $\text{CO}_2$ . Particulates, in the form of carbonaceous soot, have been a concern for decades; originally, attempts were directed toward reducing the visible smoke emitted with the exhaust. These particulate emissions have typically been reported as an SAE "smoke number" (SN) (20) that can be related to total particulate mass fairly reliably (24) but, when particle size distributions, number densities, and CN activity are needed, this approach to measurement is not adequate. More detailed sizing measurements have been performed (25), but are not routine.

Chemiluminescence detectors have been used to measure  $\text{NO}$  as well as  $\text{NO}_x$ . For  $\text{NO}_x$  measurements, the  $\text{NO}_2$  fraction of the  $\text{NO}_x$  is first converted to  $\text{NO}$ , and the chemiluminescence generated when the net  $\text{NO}$  reacts with ozone is quantified (19).  $\text{NO}_2$  is determined as the difference between an  $\text{NO}$  measurement and the corresponding  $\text{NO}_x$  measurement.  $\text{NO}_x$  measurements have conventionally been reported as the total mass of  $\text{NO}_2$ , plus the mass equivalent of  $\text{NO}$  oxidized to  $\text{NO}_2$ . Thus,  $\text{NO}_x$  is conventionally reported as the  $\text{NO}_2$  gram equivalent of the total measured species (19,26), independent of the oxidation state (even though it is, typically, mostly  $\text{NO}$  near the exit of gas turbine engines). This convention, unfortunately, has not always been stated explicitly, generating some confusion in interpreting these numbers in the broader community. In this chapter,  $\text{NO}$ ,  $\text{NO}_2$ , and  $\text{NO}_x$  emissions will all be reported as gram equivalents of  $\text{NO}_2$ . Generally, other  $\text{NO}_y$  species (e.g.,  $\text{HNO}_3$ ) have not been measured to determine whether significant levels are present.

While chemiluminescent  $\text{NO}_x$  measurements have been, and continue to be, the standard  $\text{NO}_x$  measurement technique, ultraviolet absorption measurements of  $\text{NO}$  were made as part of the CIAP program (27). A big discrepancy was observed between  $\text{NO}$  measured using absorption and  $\text{NO}_x$  quantified by collecting exhaust with a relatively crude probe and analyzing it with a chemiluminescent instrument; the UV absorption was as much as 4 to 5 times greater than the chemiluminescent  $\text{NO}_x$  measurement (28). This discrepancy was biggest in high-temperature and high-velocity flows such as those that would be encountered in the supersonic exhaust from any HSCT engine. Improvements in probe design and line-of-sight measurement methods may allow these differences to be resolved, but apparently there is no quotable reference study that addresses the discrepancies between optical and sampling measurements. Given the need for accurate and reliable emissions estimates for modeling the stratospheric impact of these vehicles, these differences must be understood and an optimal measurement strategy adopted.

Flame ionization has been used to quantify the THC, while nondispersive infrared techniques are used to measure CO, CO<sub>2</sub>, and water vapor (19). The amount of SO<sub>2</sub> emitted is directly related to the sulfur content of the fuel and, thus, is not controlled by combustor design. When SO<sub>2</sub> is measured, a nondispersive ultraviolet technique is employed. The SAE SN is measured for particulates emissions by collecting particles as a known volume exhaust sample is drawn through a filter and quantifying the change in the filter's reflectance (20).

Radical species, particularly OH, may be chemically active in the exhaust leaving the engine nozzle. Although it is not one of the standard exhaust species usually reported, superequilibrium OH concentrations were measured in the exhaust of a turbojet for supersonic flight conditions during CIAP (27). The observed superequilibrium ratio was large (>10) in non-afterburning operation, but approached unity for afterburning cases. Thus, OH concentrations and chemical effects are expected to depend on engine configuration and cycles (duct-burning versus turbofan/turbojet). If an important role in exhaust chemical processing of NO<sub>y</sub> and CN is established, some reliable measurement of OH would be necessary.

The measurement of a species in the exhaust flow determines its local concentration or mass fraction, but with the variety of combustor designs, engine cycles, and bypass ratios currently under consideration for these engines, different amounts of air end up in the exhaust for a given fuel flow rate. It has been convenient to normalize the emission rate, on a mass basis, of a given species by the mass flow rate of fuel. Thus, an emission index (EI X) is defined as

$$EI_{(Y)}X = \frac{(\text{g/s species X})}{(\text{kg/s fuel})} \quad (1)$$

Emissions expressed as volume fractions require conversion using species molecular masses (19) to arrive at an EI. For nearly complete combustion, calculation of an EI effectively normalizes by the rate of enthalpy addition to the air, as it passes through the engine.

The preceding subscript (Y) is not a standard notation, but it will be used in this chapter to indicate that the EI of species X is being reported as the mass equivalent of species Y. This notation resolves any possible ambiguities associated with reporting NO<sub>x</sub> EIs and allows the reporting convention, in terms of NO<sub>2</sub>, to be explicit. THC is also a mixture of compounds, and its EIs are reported in terms of CH<sub>2</sub>, CH<sub>α</sub> (where α is the fuel atomic hydrogen/carbon ratio) (19), or CH<sub>4</sub>; the latter will be used here. A missing preceding subscript for a pure species will be taken to mean that its emission index is expressed in terms of its own mass, i.e., Y is identical to X. Clearly, EIs can only be meaningfully summed if the subscripts match.

It is worth emphasizing that the normalization used in defining the EI does not account for propulsion efficiency and so does not represent the best overall reduction of net emissions from an engine. For instance, if a particular scheme reduced EI<sub>(NO<sub>2</sub>)</sub>NO<sub>x</sub> by 10% but required a 15% greater overall fuel flow rate to achieve the same thrust, there would be a penalty resulting from poorer fuel consumption as well as the increase in emissions. The Environmental Protection Agency parameter for landing-takeoff cycle conditions (29) represents a means of including the propulsion performance in the emissions estimation method. A similar approach could be used to compare engines in supersonic cruise operation for assessment of an HSCT's impact on the stratosphere.

Further, the total performance of the aircraft is not being considered; the most likely relationship is that a heavier aircraft results from emission reduction procedures (12-14). An increase in aircraft weight translates into more fuel burned and, thus, an increase in net emis-

sions for a given EI. Therefore, the net emissions from an HSCT will depend on the total aircraft design, not simply on an EI. On the other hand, combustor emissions performance will be optimized by lowering the important EIs and, since improved combustor design will lower NO<sub>x</sub> emissions for any given propulsion system or airframe configuration, lowering EIs is a key factor in improving the overall emissions performance of an aircraft.

## NO<sub>x</sub> ESTIMATION METHODS

Extensive NO<sub>x</sub> emissions measurements have been performed over the years on many engines and engine components. Development work is proceeding toward a "low NO<sub>x</sub>" HSCT combustor, but a complete prototype engine is still a long way from the test cells. Estimates for the expected emission performance of a given design are calculated by using semi-empirical correlations that have been developed and refined in the past emission measurement programs. These correlations account for the experimentally observed pressure and temperature dependences of the net NO<sub>x</sub> emission for a given combustor. Insofar as changes in combustor design do not alter the overall chemical kinetics, the correlations can be used to guide the combustor development efforts.

The essentially square-root dependence of EI(NO<sub>2</sub>)NO<sub>x</sub> on combustor pressure and the exponential dependence on combustor inlet temperature were used in correlations for CIAP work, and current correlations have evolved from them. Over the range of combustor designs measured to date, these dependencies have been demonstrated to fit the observed data well, with a single multiplicative coefficient reflecting a given combustor's overall emission performance. For example, GE Aircraft Engines (GEAE) uses a correlation:

$$EI_{(NO_2)}NO_x = 0.0986 \left[ \frac{p_3}{1 \text{ atm}} \right]^{0.4} \exp \left( \frac{T_3}{194.4 \text{ K}} - \frac{H_0}{53.2 \text{ g H}_2\text{O/kg dry air}} \right) \quad (2)$$

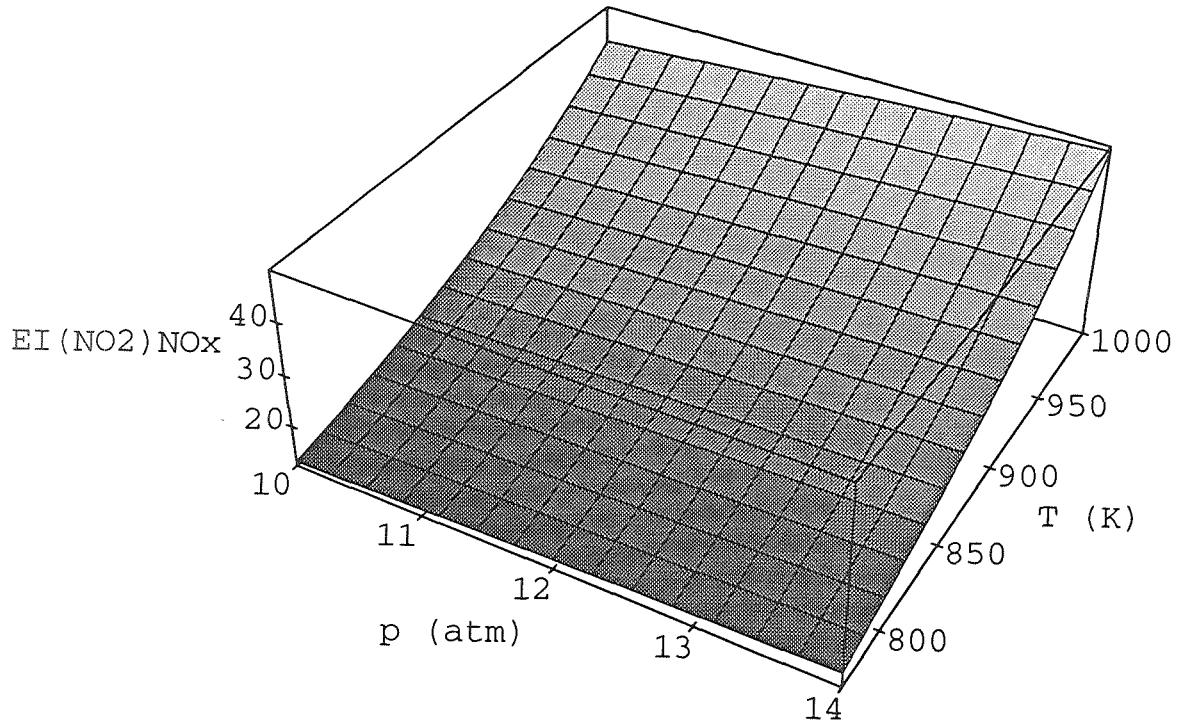
for their "dual annular" low NO<sub>x</sub> combustor for the NASA Experimental Clean Combustor Program (ECCP) (30). In the correlation,  $p_3$  is the combustor inlet pressure, and  $T_3$  is the combustor inlet temperature. The effect of ambient humidity  $H_0$  is to reduce NO<sub>x</sub> production, but at the low humidity levels encountered in the stratosphere, this correction will be negligible. GEAE's previous combustors used in the CF6 series engines are also approximated by this correlation, with the multiplicative constant (0.0986) increased by 25% and a constant value of 2.2 added to the entire expression for the CF6-80C, and a 35% increase and 1.7 added for the CF6-50C.

The coefficient of GEAE's correlation is affected by the specific combustor design, including the residence time that a parcel of reacting fluid remains within the combustor. This particular effect is included parametrically in the correlations of Pratt and Whitney and NASA by referencing a representative combustor velocity. These two correlations are the same, except that NASA's does not correct for water vapor effects; both include a reciprocal reference velocity,  $V_{\text{ref}}$ , dependence appropriate to the combustor flow and a dependence on  $T_4$ , the combustor exit temperature, reflecting the temperature rise resulting from combustion heat release.

$$EI_{(NO_2)}NO_x \sim \frac{p_3^{0.5} T_4}{V_{\text{ref}}} \exp \left( \frac{T_3}{288 \text{ K}} - \frac{H_0}{53.2 \text{ g H}_2\text{O/kg dry air}} \right) \quad (\text{P\&W}) \quad (3)$$

$$EI_{(NO_2)}NO_x \sim \frac{p_3^{0.5} T_4}{V_{\text{ref}}} \exp \left( \frac{T_3}{288 \text{ K}} \right) \quad (\text{NASA LeRC}) \quad (4)$$

The general functional dependence of these correlations is shown in the figure below, where  $EI_{(NO_2)NO_x}$  is plotted using the GEAE correlation for pressures from 10 to 14 atmospheres and temperatures between 770 K and 1000 K. Pratt and Whitney's and NASA's correlations have a similar functional form for reasonable values of  $T_4$ , allowing for the combustion heat release and overall equivalence ratio. For  $T_4 \sim T_3 + 1100$  K, a multiplicative constant can be chosen for the Pratt and Whitney NASA correlation so that the temperature and pressure dependences agree with the GE correlation within 5% to 10%.



**Figure 1.** GEAE's correlation of  $EI_{(NO_2)NO_x}$  as a function of  $10 \text{ atm} \leq p_3 \leq 14 \text{ atm}$  and  $770 \text{ K} \leq T_3 \leq 1000 \text{ K}$  for the ECCP technology combustor.

For estimating  $EI_{(NO_2)NO_x}$  for the Lean, Premixed, Prevaporized (LPP) combustor, GEAE uses the correlation: (31)

$$EI_{(NO_2)NO_x} = t_{res} \exp\left(-72.28 + 2.8 T_{adia}^{0.5} - \frac{T_{adia}}{38.02}\right), \quad (5)$$

where  $t_{res}$  is the combustor residence time in milliseconds and  $T_{adia}$  is the adiabatic flame temperature expressed in kelvins.

These correlations are used to estimate the emissions performance of a combustor for conditions that have yet to be tested. Indeed, the most promising candidate  $NO_x$  reduction schemes have not yet been tested at the conditions expected in HSCT combustors. Promising experiments (32) indicate that advanced combustor concepts may achieve significant reductions at  $p_3, T_3$  appropriate to HSCT engine cycles. However, this indication is based on experiments at less severe operating conditions extrapolated to the desired  $p_3, T_3$ . Future experiments will clarify the performance of this combustor approach at the anticipated HSCT conditions and further test the correlations for an as-yet-uncalibrated technology.

## EMISSION INDICES

Emission indices were measured for several engines intended for supersonic flight during the 1970s (18,33,34). Some of the results of this time period are shown in Table 1. Included are measurements of the engine of the one supersonic civilian transport that has operated commercially, the Olympus engine of the Concorde airplane. An important distinction must be made in comparing these EIs with those calculated for the proposed HSCT engine. The increased propulsion efficiency inherent in the designs for the HSCT dictates higher combustor inlet temperatures (and pressures) than were used in the 1970s engines. The amount of  $\text{NO}_x$  produced under these more severe conditions would be much greater than that measured in these earlier engines if the same combustor technology was used. Substantial improvements in the combustor design, improving the mixing, controlling the local equivalence ratio, and minimizing the residence time, are required to decrease the  $\text{NO}_x$  emissions relative to these engines while simultaneously maintaining the higher operating pressure ratios, and thus combustor inlet temperatures, necessary for the required cycle efficiency.

Table 1 also shows emissions measurements for two afterburning military turbojet engines (18,33,34). The measurements for the J58 engines were in preparation for the YF-12 in-flight  $\text{NO}_x$  field measurements. The study of these engines demonstrated trends of EIs versus altitude, fuel-air ratio, Mach number, and the presence or absence of afterburning for a specific engine. The optimized design of an engine designed to fly within a narrow range of flight conditions may not necessarily reflect all of these trends, however.

While it is significant that  $\text{EI}(\text{NO}_2)\text{NO}_x$  was reduced by a factor of  $\sim 2$  during afterburning operation, this cannot be employed as a reduction method for HSCT propulsion. The reduction occurs because the afterburning fuel is consumed at lower pressure and temperature after expansion through the turbine, but this is coupled to increased EI CO, EI THC, and, most notably, substantial increases in specific fuel consumption and, possibly, more total  $\text{NO}_x$  produced. Increases in specific fuel consumption, in particular, could not be tolerated for sustained supersonic cruise in an economically viable commercial aircraft.

**Table 1.** Measured 1970s Supersonic Engine Emission Indices

Measured 1970's Supersonic Engine Emission Indices			
Species	Olympus 593 <sup>18</sup>	YJ93-GE-3 <sup>18</sup>	J58 <sup>33,34</sup>
CO	1.4 - 4.6	3.4 - 38.7	1 - 120
$(\text{NO}_2)\text{NO}_x$	17 - 20	1.81 - 12.03	2 - 20
$(\text{NO}_2)\text{NO}$	16 - 19	1.83 - 10.69	
$\text{NO}_2$	0.2 - 1.3		
$(\text{CH}_4)\text{THC}$		0.03 - 0.8	0.03 - 12

Pratt and Whitney's calculated emissions performance for their proposed Turbine Bypass Engine (35) is included in Table 2. General emissions levels are given, but engine cycles have been optimized to different degrees for each case so, for example, the fact that  $\text{EI}(\text{NO}_2)\text{NO}_x$  is slightly greater for Mach 2.4 should not necessarily be construed as indicative of greater  $\text{NO}_x$  emissions for that case. The changes in  $\text{CO}_2$  and  $\text{H}_2\text{O}$  emissions at Mach 3.2 relative to the lower speeds are due to a fuel change. The higher-velocity flight conditions require a different fuel (JP-7 instead of the more commonly used Jet A) with a higher thermal stability



and a concomitant increase in the H/C and H<sub>2</sub>O/CO<sub>2</sub> ratios. The soot/particulate EI is calculated from the SAE SN. This is a quantitative measure of particulate emissions, but is not based on direct measurement of the emitted particulate mass (20). The calculated emissions performance of GEAE's Variable Cycle Engine (36) is quantified in Table 3. The NO<sub>x</sub> emissions were based on the correlation of equation 5.

**Table 2.** Pratt and Whitney Estimates for Engine Emissions Indices (35)

Pratt and Whitney Estimates for Engine Emission Indices <sup>35</sup>			
Species	Mach 1.6 18.3 km	Mach 2.4 19.8 km	Mach 3.2 21.3 km
CO <sub>2</sub>	3165.5	3165.5	3117
H <sub>2</sub> O	1233	1233	1350
CO	1.1	1.3	1.9
(NO <sub>2</sub> )NO <sub>x</sub>	5.3	6.4	5.1
(NO <sub>2</sub> )NO	4.5	5.4	4.3
NO <sub>2</sub>	0.8	1.0	0.8
SO <sub>2</sub>	1.0	1.0	1.0
soot/particulates	0.02	0.02	0.02
(CH <sub>4</sub> )THC	0.1	0.1	0.2
SAE Smoke Number	18.4	19.7	14.0
Fuel	Jet A	Jet A	JP-7

**Table 3.** GE Aircraft Engines Estimates for Engine Emission Indices (36)

GE Aircraft Engines Estimates for Engine Emission Indices <sup>36</sup>		
Species	Mach 2.4 16.8 km	Mach 3.2 21.3 km
CO <sub>2</sub>	3156	3135
H <sub>2</sub> O	1240	1290
CO	< 5	< 6
(NO <sub>2</sub> )NO <sub>x</sub>	5.7	7.0
(NO <sub>2</sub> )NO	5.1	6.3
NO <sub>2</sub>	0.6	0.7
SO <sub>2</sub>	1.2	1.2
soot/particulates	–	–
(CH <sub>4</sub> )THC	< 0.1	< 0.1
SAE Smoke Number	≪1	≪1
Fuel	Jet A	JP-7

MTU Motoren- und Turbinen-Union in Munich Germany estimates emissions performance of HSCT engines (37) for both existing and expected future technology as indicated in Table 4.

**Table 4.** MTU Estimates for Engine Emission Indices (37)

MTU Estimates for Engine Emission Indices <sup>37</sup>		
Species	Mach 2 14.8 – 18.2 km	Mach 3 19.9 – 23.6 km
Advanced Proven Technology		
CO	4.0	4.0
(NO <sub>2</sub> )NO <sub>x</sub>	26 – 21	19 – 15
(CH <sub>4</sub> )THC	0.4	0.4
Future Technology (15 to 20 years)		
CO	2.6	2.6
(NO <sub>2</sub> )NO <sub>x</sub>	11 – 9	8 – 7
(CH <sub>4</sub> )THC	0.3	0.3

In CIAP, consensus predictions were formulated (38) for exhaust emissions for anticipated emission reduction technologies to be used in the SST program. Those predictions were for technological development that was never pursued to the point of demonstration of its potential. However, they serve as a point of reference for current predictions and are included in Table 5. The last column in Table 5 gives the range of EIs under consideration for preliminary assessments.

The range of CO<sub>2</sub> and H<sub>2</sub>O emissions is purely a function of fuel composition, changes in these emissions are related to changes in fuel composition that increase its thermal stability, as becomes necessary around Mach 3. SO<sub>2</sub> is also a function of the fuel itself, all the fuel sulfur is believed to be emitted as SO<sub>2</sub>. Carbon monoxide and total unburned hydrocarbons (THC) emission estimates will have a broad range, as long as both duct burning and unaugmented turbojet or low-bypass turbofan options are being considered, but are nonetheless bounded by fuel consumption constraints for an economically viable vehicle.

NO<sub>x</sub> emissions have the most extensive range, as well as the greatest possibilities for control within the operational envelope that an HSCT will function. The upper limit is conservative, in the sense that it uses an estimate made with the GE correlation for the GEAE/NASA ECCP combustor for which measurements have been made. The low value of 5 is not a firm prediction of future technology but, rather, an HSRP goal. These low values make use of extrapolations employing the correlations and basic laboratory data, sometimes using gaseous fuel experiments (31), to estimate the best performance foreseeable at this time. It is hoped that, in the course of the current HSRP effort, these ranges in particular can be narrowed.

## AIRFRAME EMISSIONS

The exhaust from the engines represents the largest amount of material that is left in the flight path by an airplane. However, the exhaust species that are directly involved in ozone

**Table 5.** Estimates for HSCT EIs in the Stratosphere

Estimates for HSCT EIs in the Stratosphere			
Species	CIAP Turbojet <sup>38</sup>	CIAP Duct-burning <sup>38</sup>	HSRP/AESA Current Range
CO <sub>2</sub>			3120 – 3170
H <sub>2</sub> O			1230 – 1350
CO	3	15 – 30	1.1 – 6
(NO <sub>2</sub> )NO <sub>x</sub>	3 – 14	3 – 12	5 – 50†
(NO <sub>2</sub> )NO			4 – 45†
SO <sub>2</sub>			0 – 1
soot/particulates	0.02	0.02	—
(CH <sub>4</sub> )THC	0.1 – 0.5	3 – 10	<0.1 – 0.2

†The upper value represents existing proven technology that is not likely to be used in its current form in a future HSCT aircraft.

chemistry are trace species. Because they comprise a small fraction of the total exhaust mass, the relative amounts of other minor emissions from the proposed HSCT need to be quantified to evaluate their potential contribution to the total aircraft emissions. These additional airframe emissions, as distinguished from the engine emissions contained in the exhaust, originate from (1) aircraft systems involved in controlling or supporting flight operations and (2) passenger systems providing services on board. Estimates for these two classes of emissions for an HSCT will be made in the following subsections.

The various fluids carried on the aircraft could potentially leak from the vehicle and find their way into the atmosphere. In making the following estimates, some worst-case assumptions will be made by assuming that an estimate for a fluid loss corresponds to an emission into the stratosphere. In fact, lost fluid could remain primarily within the aircraft, and any portion that escapes may do so when the plane is on the ground or during takeoff, landing, or while passing through the troposphere. The emissions escaping the vehicle at high-altitude cruise could settle out of the stratosphere without vaporizing at the low temperatures (200-250 K) encountered. The estimates given are intended to provide a crude upper bound for the quantities of these species that might be released in the stratosphere. If any of these estimates suggests that an airframe emission species is important to stratospheric chemistry, more refined quantitation would be required to model its effects.

Since the exhaust emissions are reported as EIs in grams of emitted species per kilogram fuel burned, a comparison of those exhaust EIs and the aircraft emissions requires a correspondence relating these two quantities. Aircraft emissions are not caused by the consumption of fuel in any direct sense but, rather, are associated with (1) routine operation, and thus flight time or number of flights, or (2) random, unusual events that have some low frequency of occurrence. Conversion of these aircraft emissions to an equivalent emission index (EEI) will be made by using an estimate of the fuel burn rate appropriate for the generalized design of a Mach 2.4 HSCT aircraft and making the conversion from time to fuel mass.

## Aircraft Systems

All the mechanical and electrical systems needed to control an HSCT in flight have not yet been designed in detail, so the amounts of materials carried on board or used during operation cannot be specified. Corresponding quantities from existing aircraft cannot be substituted without qualification, since particular systems can be highly configuration-dependent; beyond that, the HSCT is a substantially different vehicle from a subsonic aircraft; thus, its systems may differ significantly from those aircraft for which quantities are available. On the other hand, the types of systems needed are basically the same as those currently in use, and available information on existing aircraft can be used to provide crude estimates of emissions resulting from these sources.

The most ample fluid carried is, of course, the engine fuel. The economical use of fuel is a driving criterion in designing the aircraft, so little unburned fuel is allowed to escape from the aircraft. Fuel is dumped, very occasionally, if too much is carried for a safe landing, but this is an emergency measure performed when approaching a landing and the aircraft is below about 2 km. Thus, fuel is not dumped in the stratosphere. Fuel tanks may be vented during flight, releasing some vaporized fuel, and this may be a bigger factor for a supersonic aircraft with significant skin heating than it is for subsonic aircraft, but no estimate for such vapor loss has yet been obtained.

Hydraulic fluid is used to control mechanical devices in the aircraft, and regular maintenance requires replenishing the hydraulic system reservoirs. Boeing (39) estimates that regular seepage or leakage amounts to 20 gallons (70 kg) of hydraulic fluid (composed of phosphate esters) lost from the hydraulic systems per year per airplane. In addition, aircraft are designed with redundant hydraulic systems to ensure control in the event that one system fails. Failures are rare events; even so, an estimate of an average loss rate by Boeing (39) is 1 gallon (3 kg) per year per airplane as a result of system failure. (This is based on a loss of 6 gallons of fluid on average in an event that occurs 50 times in  $10^6$  flight hours, as extracted from reliability reports for existing subsonic commercial aircraft, and 3311 flight hours per year per airplane for these subsonic transports.) While it will be assumed that these 70 kg per year per airplane (or  $2 \times 10^4$  kg/  $10^6$  flight hours) of phosphate esters are deposited in the stratosphere, for the low-vapor-pressure hydraulic fluids especially, it is not likely that this emission could appear in the stratosphere as a chemically reactive species.

Oil is used as a lubricant for the engines as well as some auxiliary devices; infrequently, some oil is discharged after an accidental leak. Some oil/air mist may be vented from the oil reservoir tanks (40). Some oil is consumed within the engine as well: some is burned in the combustor, some exits with the exhaust. The emissions that result from oil consumed within the engine would be quantified in a measurement of the total exhaust emissions and, thus, in fact represent an engine emission that is indiscernible from the emissions caused by fuel consumption. It is worth noting, however, that as an engine ages, changes in oil consumption may result in changes in exhaust emissions as well.

Accidental leakage of oil, like that of hydraulic fluid, will not necessarily leave the aircraft, nor will any oil that leaves necessarily remain in the stratosphere. However, as an upper bound, Boeing (39) cites a value of five incidences in  $10^6$  flight hours, each releasing an average 20 kg of oil. This amounts to a loss of 0.3 kg per year per aircraft of a fluid composed primarily of long-chain aliphatic hydrocarbons, with trace additives of phosphate esters and metal compounds.

Other less quantifiable emissions (41) could arise from the venting of the lead-acid and/or nickel-cadmium batteries used for reserve power; this would result in negligible amounts

of  $H_2$  and  $O_2$  being released. (The amount of emissions resulting from mists of KOH and  $H_2SO_4$  electrolytes would be even smaller and not likely to leave the aircraft.) Auxiliary power units (APUs) are small gas-turbine engines that would not be used in cruise typically and would emit much smaller amounts of an exhaust that is not unlike that from the main engines. Windshield washer fluid is more likely to be used at lower altitudes, and the glycol solution used is unlikely to result in even a small fraction of the "blue ice" emissions (see below). Finally, novel anti-icing techniques may make use of glycol solutions that would be carried on board, although not used in the stratosphere above hazardous clouds, but emissions from this fluid, too, are not expected to amount to any more than the "blue ice" fluids at stratospheric altitudes.

## Passenger Systems

A variety of systems within the airplane's cabin are devoted to serving the passengers on board. Several refrigeration systems are typically available for air conditioning, refrigeration of food and drink in the galley, and sometimes cooling of avionics (more correctly categorized as an aircraft system requirement). Until replacement refrigerants are found, these systems will contain CFCs, and any leakage that exits the aircraft in the stratosphere will be depositing CFCs where they are photochemically active. Douglas (41) estimates that 0.2 kg per year per airplane is typically used to maintain a representative aircraft's refrigerant systems.

Galley cooling and avionics cooling do not necessarily require CFC-based refrigeration (recirculating liquids are currently employed in some situations), so the amount of refrigerant aboard a yet-to-be-developed airplane could be minimized, if direct deposition in the stratosphere must be minimized. In a similar vein, fire extinguishers on current aircraft contain halons (41), a source of bromine and chlorine when photochemically activated in the stratosphere. Whether there is any greater risk from stratospheric flight with CFCs and halons (or their replacements) than flight in the upper troposphere with existing aircraft would determine the need for replacement or tighter control of leaks and accidental release on board an HSCT. For long-lived halocarbons, the consequences of release in the lower stratosphere are not substantially different from release at the surface. Furthermore, the current Montreal Protocol will lead to the phase out of CFCs and halons by the year 2000, and thus, refrigeration and fire extinguishers on the HSCT fleet will use available alternatives.

Lavatory holding tanks have received some media attention over the past several years as a result of mishaps attributed to "blue ice," lavatory fluid that has leaked from the holding tank as a result of faulty maintenance, frozen in the cold atmosphere, and then broken free. This has caused damage to aircraft when it was ingested in the engine or to property on the ground after impact. From the point of view of safety, this is a major problem, and efforts have been made to eradicate totally any possibility of leakage. As far as emissions are concerned, the low (and probably decreasing) frequency of occurrence and the likely substantial descent before complete vaporization suggest that lavatory fluids will not contribute to total aircraft emissions in the stratosphere. Based on one incident involving 30 kg per  $10^6$  flight hours, Boeing (39) estimates that less than 1 cup of fluid is lost per year per aircraft, using current reliability data.

For subsonic aircraft, oxygen service is available for passengers "in the event of sudden loss of cabin pressure." While this service is seldom used, some system leakage might occur from gaseous systems (42) (used for crew and perhaps passengers for high-altitude flight). Chemical  $O_2$  generation packs (43), as used in many subsonic airplanes would only emit during use. Purity requirements for passenger respiration units limit  $Cl$ ,  $CO$ , and  $CO_2$  levels to 0.1, 20, 1000 ppmv respectively, so even if these units are used, only oxygen with trace impurities is released. However, oxygen is a major atmospheric constituent, and even a major release of gas from the emergency oxygen system could not affect stratospheric chemistry. The substantially lower static pressures in the stratosphere necessitate more sophisticated depressurization

safety measures for HSCTs. Potential emissions from such safety systems must be evaluated, particularly if they use fluids not already employed in other systems.

### Calculation of Equivalent Emission Indices (EEIs) for Airframe Emissions

To compare the amounts of these airframe emissions with those from the engine, an EEI will be defined. Simply, the average emission amount in grams released in a given flight time will be divided by the total amount of fuel used during cruise in the same time period, i.e.:

$$EEI\ X = \frac{\text{average emission rate of X g/s}}{\text{fuel burn rate kg/s}} \quad (6)$$

Using the total of 3311 flight hours per year per aircraft for existing subsonic aircraft (as used above) to arrive at a mean emission rate from the subsonic reliability data, and taking a fuel burn rate of 9 kg/s as representative for Mach 2.4 flight, the emission estimates noted above can be converted to EEIs for HSCT cruise; these are listed in Table 6. Note that a similar value of 3100 stratospheric flight hours is considered representative for HSCT flight (39) as well. Again, it is assumed that all the lost fluids are emitted and vaporized in the stratosphere which, in many of these cases, is not likely to happen; so these quantities should be interpreted as upper-bound estimates.

**Table 6.** Upper Bound Estimates for Airframe Emissions in the Stratosphere

Upper Bound Estimates for Airframe Emissions in the Stratosphere		
Emission	kg / 10 <sup>6</sup> flight hours	Equivalent Emission Index
<b>Aircraft Systems</b>		
lubrication oil burst	1 × 10 <sup>2</sup>	3 × 10 <sup>-6</sup>
hydraulic fluid burst	1 × 10 <sup>3</sup>	3 × 10 <sup>-5</sup>
hydraulic fluid leaks	2 × 10 <sup>4</sup>	5 × 10 <sup>-4</sup>
fuel dump	n/a†	n/a†
fuel vent	no estimate	no estimate
<b>Passenger Systems</b>		
refrigerants	1 × 10 <sup>2</sup>	4 × 10 <sup>-6</sup>
'blue ice'	30	1 × 10 <sup>-6</sup>

†Not applicable. Fuel is not dumped at stratospheric altitudes. Corresponding tropospheric quantities would be 3 × 10<sup>6</sup> kg / 10<sup>6</sup> flight hours, EEI = 0.1 (39).

Tables 2-4 show that the largest stratospheric emission from the airframe is substantially less than the smallest emission from the engine and several orders of magnitude less than NO<sub>y</sub> emissions. Since the airframe emissions are upper-bound estimates, it appears that these airframe emissions can be neglected, relative to those from the engine. Two notable exceptions might be refrigerants and gaseous fire extinguishers; if these species are highly photochemically active, the effects of direct deposition in the stratosphere would need to be assessed. If there are no highly reactive catalytic effects from any of the other airframe emissions, it appears that their contribution to the net aircraft emissions can be neglected.

## CONCLUDING REMARKS

Estimates have been provided for the emissions from a proposed HSCT in stratospheric flight. The emissions from the aircraft are expected to be dominated by the effluents from the engine; emissions from the airframe are probably negligible. Current estimates for the  $\text{NO}_x$  emissions have been calculated by engine companies for the proposed engine cycles using correlations that have been developed over the past several decades of  $\text{NO}_x$  reduction programs. These estimates will have to be validated with future tests of components and full engines as development proceeds.

More complete measurements of particulate size distributions and number densities, and of aerosol-active species, will be required if heterogeneous chemistry is to be accurately modeled, both in the wake of individual airplanes and globally. New measurements of  $\text{NO}_y$  speciation will be necessary to catalog the "odd-nitrogen" emissions completely and to resolve uncertainties in measuring high-temperature, high-velocity exhaust gases with a sampling probe.

## ACKNOWLEDGMENTS

The author would like to thank the contributors for their materials and discussions concerning their contributions and R. W. Niedzwiecki and J. D. Holdeman of NASA Lewis Research Center for references and useful discussions. Many useful comments and suggestions were received from the several reviewers of an earlier draft of this chapter.

## REFERENCES

1. Johnston, H., Reduction of stratospheric ozone by nitrogen oxide catalysts from supersonic transport exhaust, *Science*, 173, 517-522, 1971.
2. Barrington, A.E., ed., Climatic Impact Assessment Program, Proceedings of the Survey Conference, February 15-16, 1972, DOT-TSC-OST-72-13, 1972.
3. Broderick, A.J., ed., Proceedings of the Second Conference on the Climatic Impact Assessment Program, DOT-TSC-OST-73-4, 1973.
4. Broderick, A.J., and T.M. Hard, eds., Proceedings of the Third Conference on the Climatic Impact Assessment Program, DOT-TSC-OST-74-15, 1974.
5. Hard, T.M., and A.J. Broderick, eds., Proceedings of the Fourth Conference on the Climatic Impact Assessment Program, DOT-TSC-OST-75-38, 1976.
6. CIAP Monograph 1, The Natural Stratosphere of 1974, DOT-TST-75-51, U.S. Department of Transportation, Washington, D.C., 1975.
7. CIAP Monograph 2, Propulsion Effluents in the Stratosphere, DOT-TST-75-52, U.S. Department of Transportation, Washington, D.C., 1975.
8. CIAP Monograph 3, The Stratosphere Perturbed by Propulsion Effluents, DOT-TST-75-53, U.S. Department of Transportation, Washington, D.C., 1975.
9. CIAP Monograph 4, The Natural and Radiatively Perturbed Troposphere, DOT-TST-75-54, U.S. Department of Transportation, Washington, D.C., 1975.
10. CIAP Monograph 5, The Impacts of Climatic Change on the Biosphere, DOT-TST-75-55, U.S. Department of Transportation, Washington, D.C., 1975.
11. CIAP Monograph 6, Economic and Social Measures of Biologic and Climatic Change, DOT-TST-75-56, U.S. Department of Transportation, Washington, D.C., 1975.
12. Boeing Commercial Airplane Co., High-Speed Civil Transport Study, NASA CR-4234, 1989.
13. Boeing Commercial Airplane Co., High-Speed Civil Transport Study - Summary, NASA CR-4234, 1989.
14. Douglas Aircraft Co., Study of High-Speed Civil Transports, NASA CR-4235, 1989.
15. Holdeman, J.D., Dispersion of Turbojet Engine Exhaust in Flight, NASA TN D-7382, 1973.
16. Farlow, N.H., V.R. Watson, M. Loewenstein, K.L. Chan, H. Hoshizaki, R.J. Conti, and J.W. Meyer, Measurements of Supersonic Jet Aircraft Wakes in the Stratosphere, Second International Conference on the Environmental Impact of Aerospace Operations in the High Atmosphere, American Meteorology Society, Boston, pp. 53-58, 1974.
17. Hoshizaki, H., et al., in CIAP Monograph 3, Chapter 2, 1975.
18. Broderick, A.J., et al., in CIAP Monograph 2, Chapter 4, 1975.



19. Aerospace Recommended Practice ARP 1256A, Procedure for the Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines, SAE, 1980.
20. Aerospace Recommended Practice ARP 1179A, Aircraft gas turbine engine exhaust smoke measurement, SAE, 1980.
21. Spicer, C.W., M.W. Holdren, F.F. Lyon, and R.M. Riggin, Composition and Photochemical Reactivity of Turbine Engine Exhaust, ESL-TR-84-61, 1985.
22. Spicer, C.W., M.W. Holdren, S.E. Miller, D.L. Smith, R.N. Smith and D.P. Hughes, Aircraft Emissions Characterization, ESL-TR-87-63, 1988.
23. Stumpf, S.A., and W.S. Blazowski, Detailed Investigations of Organic Compound Emissions from Aircraft Gas Turbine Engines, *I.E.E.E. Annals*, No. 75CH1004-I-27-1, 1976.
24. Blazowski, W.S., and R.F. Sawyer, in CIAP Monograph 2, Chapter 3, 1975.
25. Low, H.C., C.J. Scott, and A. Veninger, Correlated Fuel Property Effects on an F402-RR-406A (Pegasus) Engine Combustor, ASME Paper 90-GT-276, 1990.
26. *Federal Register*, (July 17, 1973) Emission Standards and Test Procedures for Aircraft, Vol. 38, No. 136, 19088-19102; (July 22, 1974) Supersonic Aircraft Pollution, Vol. 39, No. 141, 26653-26655; (March 24, 1978) Control of Air Pollution from Aircraft and Aircraft Engines, Vol. 43, No. 58, 12614-12634; (December 30, 1982) Control of Air Pollution from Aircraft and Aircraft Engines; Emission Standards and Test Procedures, Vol. 47, No. 251, 58462-58474.
27. McGregor, W.K., B.L. Seiber, and J.D. Few, in the Second Conference on CIAP, 214-229, 1973.
28. Few, J.D., and H.S. Lowry III, Reevaluation of Nitric Oxide Concentration in Exhaust of Jet Engines and Combustors, AEDC-TR-80-65, 1981.
29. Jones, R.E., Gas turbine engine emissions, Problems, progress and future, *Prog. Energy Combust. Sci.* 4, 73-113, 1978.
30. Gleason, C.C., and D.W. Bahr, Experimental Clean Combustor Program (ECCP), NASA CR-135384, 1979.
31. Roffe, G., and K.S. Venkataramani, Emission Measurements for a Lean Premixed Propane/Air System at Pressures up to 30 Atmospheres, NASA CR159421, 1978.
32. Tacina, R.R., Low NO<sub>x</sub> Potential of Gas Turbine Engines, AIAA paper 90-0550, 1990.
33. Holdeman, J.D., Exhaust emission calibration of two J-58 afterburning turbojet engines at simulated high-altitude, supersonic flight conditions, NASA TN D-8173, 1976.
34. Holdeman, J.D., Measurements of Exhaust Emissions from Two J-58 Engines at Simulated Supersonic Cruise Flight conditions, ASME paper 76-GT-8, 1976.
35. Hasel, K.L.; Pratt & Whitney, East Hartford, CT; personal communication.

36. Matulaitis, J.A.; GE Aircraft Engines, Cincinnati, OH; personal communication.
37. Albers, M., and J. Hourmouziadis, MTU, Munich, FRG; personal communication.
38. Grobman, J., and R.D. Ingebo, in CIAP Monograph 2, Chapter 5, 1975.
39. Gerstle, J.H., and C. Stander, Boeing, Seattle, WA; personal communication.
40. Dagget, D.; Rolls-Royce, Inc., Atlanta, GA; personal communication.
41. Hamilton, G.L.; Douglas Aircraft Co., Long Beach, CA; personal communication.
42. Aerospace Standard AS 8010A, Aviator's Breathing Oxygen Purity Standard, SAE, 1986.
43. Aerospace Standard AS 1304, Continuous Flow Chemical Oxygen Generators, SAE, 1973.